Understanding and Approaching Fundamental Limits to Free Space Optical Communication through the Turbulent Atmosphere

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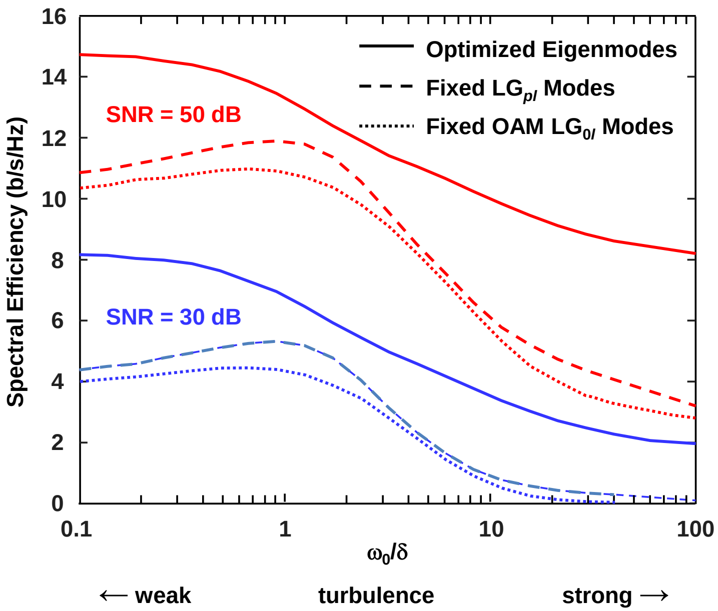
Stochastic Eigenmodes of Atmospheric Turbulence Channels

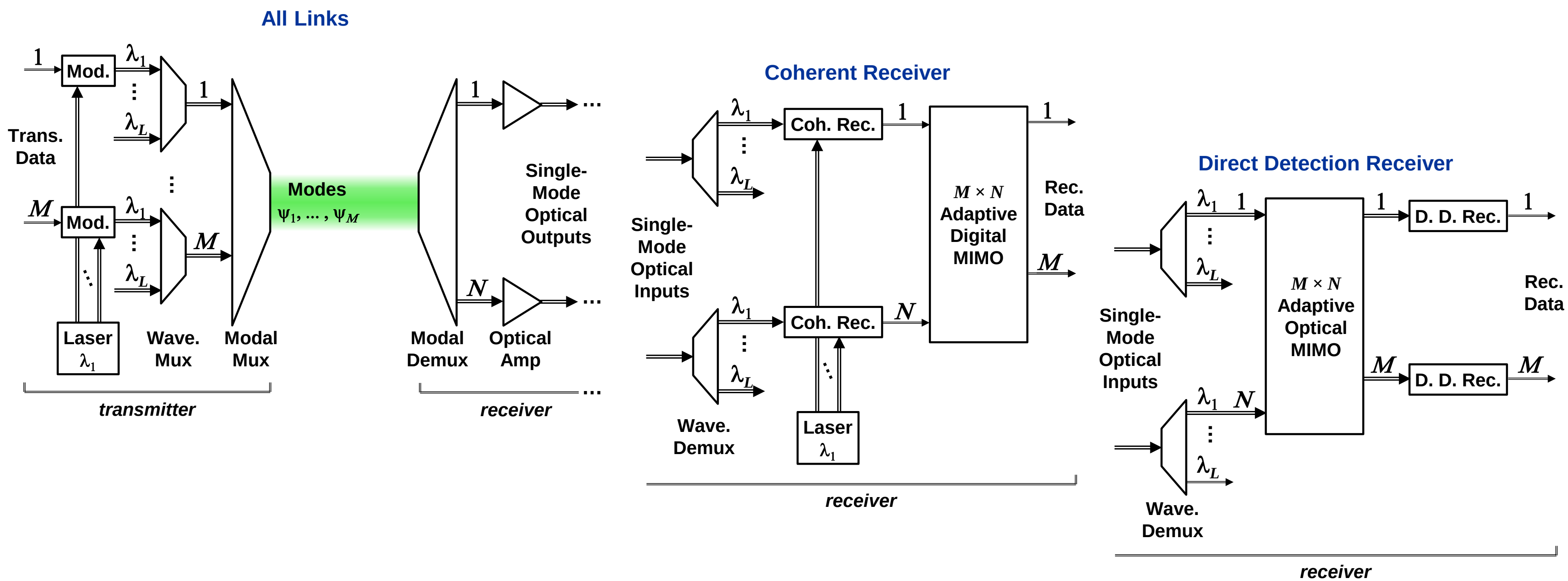
- Optimal transmit and receive basis functions.
- Subject to minimal degradation by turbulence.
- Minimize number of basis functions needed to capture a given fraction of energy in
  - Single-input multi-output (SIMO) transmission.
  - Multi-input multi-output (MIMO) transmission.
- Orthogonal mode set derived analytically using canonical turbulence model assuming
  - Transmitter knows only statistics of turbulence, i.e., received transverse coherence length.
  - Receiver knows statistics and can track instantaneous realization of turbulence.
- Can be mapped to/from single-mode waveguides by fundamentally lossless devices.

- Results
  - Near-field regime
  - Coherent detection
  - Scaled coherence length $\delta \approx r_0 / 2.62$
  - Reference beam radius ω_0
  - Signal-to-noise ratio $\gamma = P_{\text{tot}} / \sigma^2$



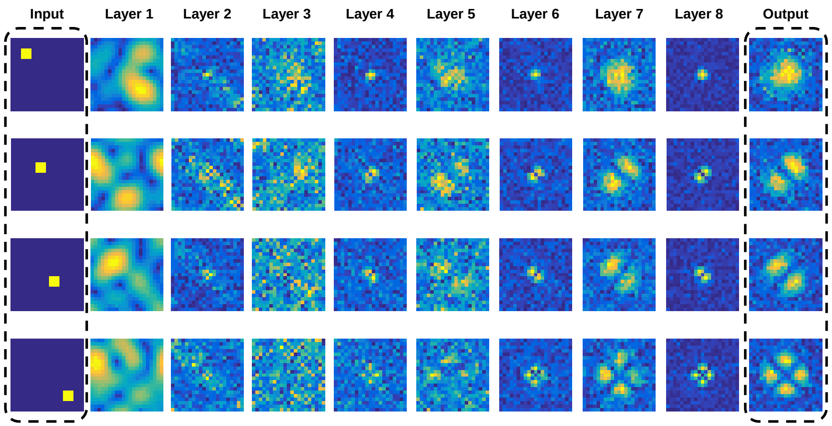
Modal Free-Space Transmission Systems

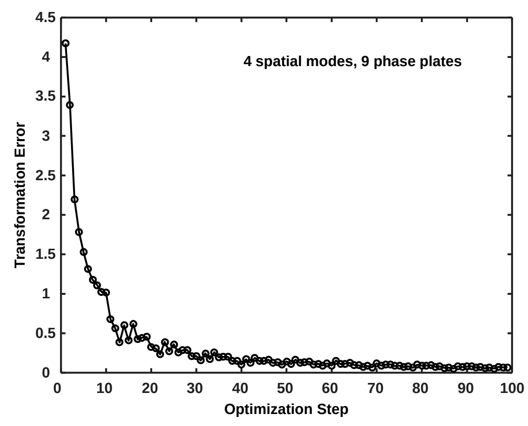
- Telescope optics not shown. Modal mux and demux may be in focal or pupil plane.
- Preference: WDM, PDM, SDM. Only one polarization and one wavelength shown.
- SIMO transmits $M = 1$ spatial mode; MIMO transmits $M > 1$ spatial modes. Transmit digital precoding (e.g., space-time coding) not shown.
- Receive N spatial modes, $N \geq M$. Use $M \times N$ processing instead of adaptive optics.
- Direct detection may place optical $M \times N$ before wavelength demux, depending on link coherence bandwidth, WDM signal bandwidth, and optical $M \times N$ device bandwidth.



Modal Multiplexers and Demultiplexers

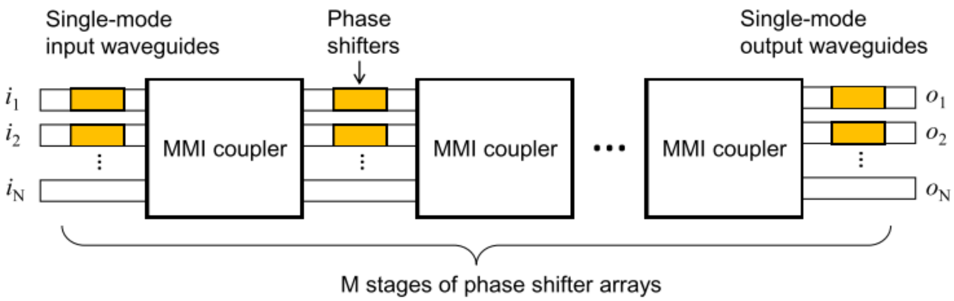
- Desired properties
  - Mode-selective: one-to-one mapping between inputs/outputs and modes.
  - Fundamentally lossless.
  - Wide optical bandwidth.
  - Programmable.
- Options
  - Mode-selective photonic lantern: S. G. Leon-Saval et al, *Opt. Express* **22** (2014).
    All-fiber device based on adiabatic mode conversion and phase matching.
    Difficult to fabricate, difficult to scale to many modes, not programmable.
  - Multi-plane light converter: G. Labroille et al, *Opt. Exp*. **22** (2014).
    Free-space device based on sequence of 2D Fourier transforms and phase plates.
    Design involves a non-convex global optimization, which was solved by simulated annealing.
- We have developed an MPLC design method converging rapidly to global optimum.

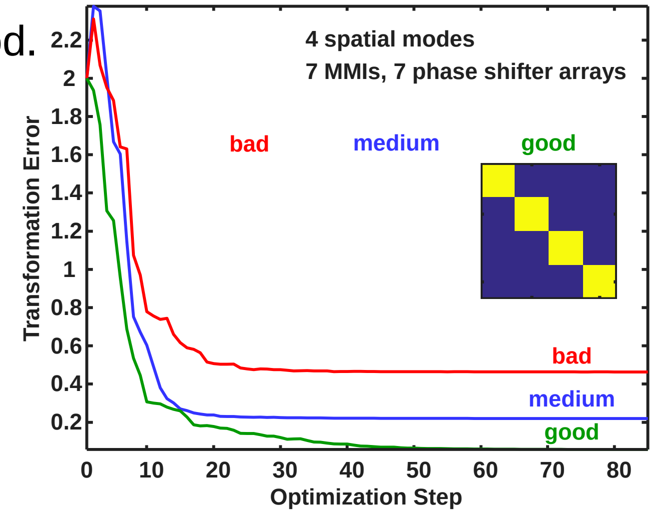




Optical Multi-Input Multi-Output Signal Processing

- Desired properties
  - Can realize an arbitrary $M \times N$ matrix.
  - Fundamentally lossless.
  - Wide optical bandwidth.
  - Adaptive to track time-varying turbulence.
- Options
  - Triangular Mach-Zehnder interferometer array: D. A. B. Miller, *Photon. Res*. **1** (2013). Adaptation by "self-configuration" enabled by embedded photodetectors, but is likely to be slow.
  - Rectangular Mach-Zehnder interferometer array: W. R. Clements et al, *Optica* **3** (2016). Cannot adapt or learn unknown phase shifts by "self-configuation".
  - Multimode interferference coupler array: R. Tang et al, *Photon. Technol. Lett*. **29** (2017). Analogous to multi-plane light converter. Small footprint, tolerant to fabrication errors. Design involves a non-convex global optimization, which was solved by simulated annealing.
- We are working on an efficient MMI array design method. It does not yet reliably converge to global optimum.





Summary

Stochastic eigenmodes of atmospheric turbulence channels

- Optimal modes to minimize degradation and minimize signal processing complexity for SIMO and MIMO links.
- We derived them analytically from a canonical turbulence model.

Modal free-space transmission systems

- May replace adaptive optics by digital or optical MIMO signal processing.
- May implement eigenmode transmission to optimize performance and minimize signal processing complexity.

Modal multiplexers and demultiplexers

- May realize: lossless, mode-selective, wide-bandwidth, programmable.
- We recently devised an efficient optimization method.

Optical multi-input multi-output signal processing

- May realize: arbitrary $M \times N$ matrix, lossless, wide-bandwidth, adaptive.
- May be possible to process multiple WDM channels in some systems.
- We are working on efficient optimization methods.